

A Refinement to the World Geodetic System 1984 Reference Frame

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BIOGRAPHIES

Michael J. Merrigan has been involved in GPS research and applications at NSWCDD since 1990. He received a B.S. in Geology from Virginia Tech in 1985 and a M.S. in Geodetic Engineering from Virginia Tech in 1990.

Everett R. Swift has been involved in GPS-related orbit and clock research and development at NSWCDD for over 22 years. He received a B.S. in Mathematics from Kent University in 1970 and an M.A. in Mathematics from Penn State in 1971.

Robert F. Wong has been involved in the production of the NIMA GPS precise ephemeris since 1993. He received a B.S. in Geophysics from the State University of New York in 1985.

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ABSTRACT

Using 15 days of Global Positioning System (GPS) pseudorange and carrier phase data collected during February 2001, a refined set of World Geodetic System 1984 (WGS 84) station coordinates for the National Imagery and Mapping Agency (NIMA) and Air Force permanent tracking stations was generated. These coordinates, designated WGS 84 (G1150), are for the current 17 NIMA and Air Force stations plus additional stations at Maspalomas, Beijing, China, Holloman AFB, Patrick AFB, Edwards AFB, Applied Research Laboratories of the University of Texas, NIMA/St. Louis, and two sites at the Naval Surface Warfare Center, Dahlgren Division. The accuracy of each station coordinate component is estimated to be on the order of one cm, one sigma. A tie to the International Terrestrial Reference Frame 2000 (ITRF2000) was achieved through

holding the coordinates of a large subset of 49 International GPS Service (IGS) fiducial sites fixed. Seven-parameter similarity transformations were computed to examine the systematic differences between station coordinate sets and between orbit estimate sets. For all cases, the transformation parameters indicated that the WGS 84 and ITRF2000 reference frames are essentially identical. Additionally, the differences between the estimated Earth orientation parameters and the International Earth Rotation Service final values were reduced. Comparisons performed against independent solutions for four NIMA and three IGS stations support the stated overall accuracy of better than one cm per component, one sigma.

INTRODUCTION

The National Imagery and Mapping Agency (NIMA) operates a worldwide network of 11 permanent Global Positioning System (GPS) satellite tracking stations. Data from these stations and the five GPS Operational Control Segment (OCS) stations operated by the Air Force along with data from an International GPS Service (IGS) station located in Maspalomas are used routinely by NIMA to generate precise GPS orbit and clock estimates for all satellites. The 11 NIMA stations are located in Australia, Argentina, England, Bahrain, Ecuador, the U.S. Naval Observatory (USNO) in Washington, D.C, Alaska, New Zealand, South Africa, South Korea, and Tahiti. The five OCS stations are located in Colorado Springs, Ascension, Diego Garcia, Kwajalein, and Hawaii. Table 1 lists the corresponding NIMA identification number for each of these 16 stations and the IGS stations operating in Maspalomas and China. The coordinates of these stations define the operational realization of the World Geodetic System 1984 (WGS 84) reference frame used by DoD for high precision geodetic applications. Refined estimates for these station coordinates tied to the International Terrestrial Reference Frame 2000 (ITRF2000) have been generated and put into operational use by NIMA and the Air Force in January 2002. This station coordinate set has been given the designation WGS 84 (G1150) and includes

a set of adopted velocities for the stations with an epoch of 2001.0. This designation indicates the coordinates were obtained through GPS techniques and were implemented in the NIMA precise GPS ephemeris production process beginning GPS week 1150.

Table 1. List of NIMA and Air Force Tracking Stations and Corresponding Identification Numbers

Station Name	NIMA Identification Number
Colorado Springs	85128
Ascension	85129
Diego Garcia	85130
Kwajalein	85131
Hawaii	85132
Australia	85402
Argentina	85403
England	85404
Bahrain	85405
Ecuador	85406
USNO	85407
Alaska	85410
New Zealand	85411
South Africa	85412
South Korea	85413
Tahiti	85414
Maspalomas	86102
China	86204

The previous set of station coordinates, designated WGS 84 (G873), was derived at the Naval Surface Warfare Center, Dahlgren Division (NSWCDD) in 1996 for the 12 NIMA and Air Force tracking stations that were deployed at that time (References 1 and 2). These coordinates had an estimated accuracy of better than five cm per component, one sigma, and an epoch of 1997.0. They were based on holding the ITRF94 coordinates of 13 globally distributed IGS fiducial stations fixed while estimating the NIMA and Air Force station coordinates. This aligned the WGS 84 reference frame with ITRF94. The first set of GPS-realized coordinates for these stations was derived in 1994 (Reference 3). The NNR-NUVEL1A plate motion model was adopted for moving the coordinates from the 1997.0 epoch to other times. Since 1996 additional NIMA tracking stations have been added, including stations in Alaska, New Zealand, South Africa, South Korea, and Tahiti. Coordinates for these sites were obtained by holding the coordinates of all of the pre-existing NIMA and Air Force stations fixed while estimating the coordinates of each new station. Since the WGS 84 (G873) coordinate set was derived, enhancements in processing techniques and improved modeling have been incorporated within OMNIS, the estimation software developed and maintained by NSWCDD and used by NIMA in the generation of the precise orbit and clock estimates (References 4 and 5). In

addition, it was realized that plate motion model errors were accumulating for some of the stations.

To ensure the highest possible degree of accuracy and stability in the WGS 84 reference frame, a joint effort between NSWCDD and NIMA was undertaken to refine the coordinates for the operational stations. The station coordinates were estimated while processing a data set that included data from 49 IGS fiducial station using a 15-day data set collected in February 2001. In this process, coordinates of a large subset of IGS fiducial stations were constrained to their ITRF2000 solutions. These coordinates are known to an accuracy of better than one cm per component, one sigma. Through application of this constraint, the resulting operational coordinates and the corresponding new realization of the WGS 84 reference frame becomes closely coincident with the ITRF2000 reference frame. Adopted velocities for each station were used to move the refined coordinates back to the 2001.0 epoch. This paper documents the task of deriving and evaluating the GPS-realized WGS 84 coordinates tied to ITRF2000 for a 26-station network. The 26 stations (see Figure 1) consist of the current 17 NIMA and Air Force stations plus additional stations at Maspalomas (an IGS site) Beijing, China (formerly operated by NIMA, now an IGS site), Holloman AFB, Patrick AFB, Edwards AFB, Applied Research Laboratories of the University of Texas (ARL:UT), NIMA/St. Louis, and NSWCDD (2 sites). Figure 2 displays the IGS fiducial station network.

DATA SET

Data were collected for a 15-day span from February 14-28, 2001. Data from the eleven NIMA and six Air Force stations consisted of 15-min smoothed pseudorange and carrier phase data. At all of the NIMA stations, a 12-channel Ashtech ZY-12 receiver was used to track all satellites in view. The Ashtech ZY-12 is a keyed receiver capable of tracking the encrypted pseudorange code broadcast by satellites in Anti-Spoofing (AS) mode. Deployed at China and Maspalomas are Ashtech Z-12 receivers, unkeyed 12-channel receivers that track the AS-encrypted pseudorange code in a codeless mode. The raw 30-sec pseudorange and carrier phase data collected remotely from these stations were obtained via *ftp* in RINEX format from the IGS Data Center. Deployed at Air Force's Colorado Springs and Cape Canaveral sites are Allen Osbourne Associates receivers. Deployed at the remaining stations are Stanford Telecommunications, Inc. receivers. Each of the Air Force stations tracked all satellites in view. All stations operate on Cesium frequency standards.

Raw 30-sec pseudorange and carrier phase data in RINEX format were obtained from all of the additional stations. All of the additional stations, except the two at

[illegible]

Figure 2. Worldwide Distribution of IGS Fiducial Stations

? IGS Station

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NSWCDD, operate with Ashtech receivers and Cesium clocks, the same as are used with the NIMA monitor stations. Ashtech Z-12 receivers with internal oscillators were used to collect data at the two NSWCDD sites. The raw 30-sec pseudorange and carrier phase data collected at China, Maspalomas, and the additional stations, except for the two at NSWCDD, were preprocessed similarly to the NIMA and Air Force data. The carrier phase data were used to smooth the pseudorange data, both already corrected for ionospheric refraction effects, to even 15-min intervals. The carrier phase data were sampled at the same 15-min intervals.

Meteorological data routinely collected at each of the NIMA sites were used. In addition, meteorological data were collected for the two sites at NSWCDD. No weather data were present with the data from NIMA/St. Louis and ARL:UT. Default weather data were used for these two sites and for Holloman AFB, Patrick AFB, and Edwards AFB. Default weather data were used for the Air Force stations.

The data for 49 IGS stations consisted of raw 30-sec pseudorange and carrier phase data in RINEX format. Data were not available from the IGS station at Perth, Australia during the entire data span. Data from all of the IGS fiducial stations were obtained via *ftp* at <ftp://cddisa.gsfc.nasa.gov/pub/gps/gpsdata/>"yyddd"/01o/. Meteorological data were available for a subset of the IGS fiducial stations and were obtained via *ftp* at <ftp://cddisa.gsfc.nasa.gov/pub/gps/gpsdata/>"yyddd"/01m/. The "yyddd" refers to a 2-digit year identifier, and a 3-digit day of the year identifier. Default weather data were used for all other IGS sites.

Data from all of the IGS stations were initially processed through a program to remove receiver-dependent biases. This is necessary when processing data from a "mix" of receiver types, as is the case with the station coordinate solution. This program, obtained from the USNO accommodates <P1-C1> biases from older, cross-correlation receiver types, including ROGUE SNR-x, AOA ICS-4000Z, and Trimble 4000 receivers. As satellite dependent biases are routinely estimated, the set of values appropriate for the span of interest was obtained. These values were obtained from <http://www.aiub.unibe.ch/ionosphere.html> or <ftp://igs.ensg.ign.fr/pub/igsdb/station/general/p1c1bias.his>.

Experiments were conducted for determining the preferred preprocessing technique appropriate for each of the IGS data types. As a result the pseudorange data derived using the carrier-aided smoothing preprocessor were merged with carrier phase data from the time tag calibration preprocessor for all of the IGS stations. In preprocessing the data from the IGS stations, it was determined that no P1 observations were present for

several of the stations. The data from these were preprocessed with C1 replacing the P1 observations. The data sets from the two NSWCDD sites were preprocessed the same as the IGS data.

STARTING STATION COORDINATES AND VELOCITIES

The GPS-realized WGS 84 (G873) station coordinates for the NIMA, Air Force, and Holloman AFB sites were used as starting coordinates. The starting coordinates for Cape Canaveral AFS, Patrick AFB, Edwards AFB, ARL:UT, and NIMA/St. Louis sites were derived by NIMA using absolute point positioning techniques. The starting coordinates for the two sites at NSWCDD were derived through relative positioning techniques. Station velocities were adopted to move all of the NIMA, Air Force, and additional stations' coordinates to each daily fit epoch. ITRF2000 velocities were used for stations collocated or in very close proximity to IGS stations, including the NIMA stations at Bahrain, USNO, Alaska, South Africa, South Korea, Tahiti, Maspalomas, all of the Air Force stations, and the stations at Cape Canaveral AFS and Patrick AFB. For the purpose of evaluating the modeling of plate motion, NIMA/St. Louis has been providing data from four GPS tracking stations at Australia, England, Ecuador, and New Zealand to Dr. DeMets at the University of Wisconsin (Reference 7). ITRF2000 velocity estimates for these four stations provided by Dr. DeMets were adopted. ITRF2000 velocities from nearby Continuously Operating Reference Stations (CORS) provided by Dr. DeMets were used for the stations at NIMA/St. Louis and ARL:UT. Jet Propulsion Laboratory (JPL) ITRF2000 velocity estimates were used for the NIMA station at Argentina and for the China station. ITRF2000 angular velocities of the North American plate relative to ITRF2000 were used to predict velocities for Holloman AFB and the two sites at NSWCDD. These were also provided by Dr. DeMets. NSWCDD derived velocity estimates for Edwards AFB based on ITRF97 position estimates over a two-year span.

The receiver, antenna type and offsets, clock type, and the distance from the physical mark to the antenna reference point (ARP) for each of the IGS stations was identified. This information was obtained from either a history of the log files for all stations located at the internet site <http://igs.ensg.ign.fr/pub/igsdb/station/general/loghist.txt> or individual log files for each station located at the internet site <ftp://igs.ensg.ign.fr/pub/igsdb/station/log/> ITRF2000 station positions and velocities for the IGS stations at the 1997.0 epoch were obtained from http://lareg.ensg.ign.fr/ITRF/ITRF2000/results/ITRF2000_GPS.SSC. The formal uncertainties for all of the fiducial stations are better than 1 cm. The L1 and L2 offsets specific for a particular antenna type were obtained from

<ftp://igs.ensg.ign.fr/pub/igs/b/station/general/antenna.gra>
or
ftp://igs.ensg.ign.fr/pub/igs/b/station/general/igs_01.pcv.
The phase center location adjustment, H_{LC} , computed using equation (1), combines the L1 and L2 phase centers for the antenna type associated with the receiver at each IGS station.

$$H_{LC} = (2.546 * H_{L1}) - (1.546 * H_{L2}) \quad (1)$$

where H_{L1} is the vertical distance from the ARP to the L1 phase center and H_{L2} is the vertical distance from the ARP to the L2 phase center.

ESTIMATION TECHNIQUE

The starting station coordinates were updated to the epoch of each daily fit using the adopted velocities for each site. All carrier phase data were converted to 15-min range differences over time before being processed further. Due to differences in the preprocessor techniques, the data preprocessed using the time tag calibration technique were corrected assuming time tags at time of reception, and the data preprocessed through the carrier-aided smoothing technique were corrected assuming time tags at the time of emission. Additionally, the data were corrected for tropospheric refraction effects, using the Saastamoinen model zenith corrections and the Neill dry and wet mapping functions, and for solid Earth tide, ocean loading, and pole tide effects on the station coordinates (Reference 6). Satellite antenna offset effects were also removed from the data. The JPL yaw attitude model, including their 6-hr precise estimates of yaw rates for satellites in eclipse, was used for the Block II/IIA satellites.

The *Multisatellite Filter/Smother (MSF/S)* system of programs within OMNIS (Reference 5) was used to simultaneously estimate station coordinate, satellite and station clock, tropospheric refraction, orbit, radiation pressure, y-axis acceleration, and Earth orientation parameters. The reference trajectories were reintegrated to include the effects of the IERS tidal potential models for solid Earth tides, ocean tides, and the pole tide. (It was later determined that the ocean tide model was implemented incorrectly. Tests were run to verify that this error did not have any significant effect on the station coordinate solutions.) The IERS anelastic tide model for solid Earth tides was used (Reference 6). A GM value of $398600.4418 \text{ km}^3/\text{sec}^2$ was used along with the EGM96 gravity field model truncated to twelfth degree and order. The Rockwell International radiation pressure model for Block II/IIA satellites, ROCK42, was used. Interpolation within a lookup table developed by Lockheed Martin was used to evaluate solar radiation pressure forces for the Block IIR satellites. Satellite masses used in the radiation pressure model were 890 kg for Block II, 970 kg for

Block IIA, and 1100 kg for Block IIR. A 5-min integration step was used and reduced to 10 sec during the sun-shadow transition for those satellites in eclipse. The reference trajectories were written at a 15-min interval. The starting Earth orientation values were derived from the NIMA predicted coefficient sets for this time period with zonal tide effects added to the predicted UT1-UTC values. Diurnal and semidiurnal Earth orientation corrections were also included. Three tropospheric refraction parameters were estimated for each station to accommodate both azimuth- and elevation-dependent variations in the troposphere. The Neill wet mapping function was used. Independent solutions for each satellite and station clock were estimated, except for the master clock, at each 15-min interval.

As the data quality for the IGS stations at FORT, HOB2, KWJ1, OHIG, and SANT was questionable, coordinate *a priori* sigmas of 10 cm were used for these stations. As the coordinates for HARB were relatively inaccurate, a coordinate *a priori* sigma of 1 km was used. The coordinate *a priori* sigma of essentially 0. was used for the remaining 43 IGS stations. The coordinate *a priori* sigma of 1 km was used for the NIMA, Air Force, and additional stations. The *a priori* sigmas for the Earth orientation parameters were 50 cm for the x and y offsets, 5 cm/day for the x and y rates, and 1 msec/day for the UT1-UTC rate.

The pseudorange data for the NIMA stations as well as three of the Air Force stations were assigned a minimum observation sigma of 50 cm. The pseudorange data for the Air Force site at Diego Garcia, one of the sites at NSWCD, and the majority of the IGS stations were assigned a minimum sigma of 100 cm. The pseudorange data for the Air Force site at Colorado Springs and the remaining IGS stations at Graz, Kerguelen, and Potsdam were assigned a minimum sigma of 150 cm. The range difference data for the NIMA and IGS stations were assigned a minimum sigma of 1 cm. The range difference data for the Air Force stations and one of the sites at NSWCD were assigned a minimum sigma of 1.5 cm.

Successive solutions and editing based upon residual tolerances were used to edit the data. Upon completion of all of the 15 daily coordinate solutions, the individual solutions were formally combined to derive the final coordinates. The corrections to the starting coordinates for the NIMA and Air Force stations for the middle day of the data span are given in Figure 3. There is a small negative bias in the east direction, a small positive bias in the north direction, and a relatively large negative bias in the up direction. Relatively large horizontal corrections are noted for the stations in Ecuador (85406) and New Zealand (85411). These adjustments reflect deficiencies in modeling the plate motion for locales adjacent to plate boundaries. The large negative bias noted in the up

direction reflects a deficiency in the previous coordinate solution. Improvements in the tropospheric refraction modeling associated with the current solution have reduced errors in this direction.

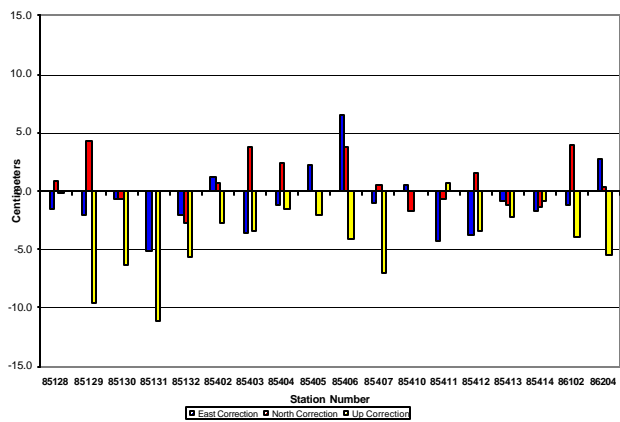


Figure 3. NIMA and Air Force Station Coordinate Corrections

The station coordinate errors are characterized in Figure 4. The accuracy of the refined coordinates is better than one cm, one sigma, in the east, north and vertical directions. Although the standard deviation of the corrections is slightly larger than one cm in the up direction, these values are conservative because the errors in the mean values should be considerably smaller. Assuming independent estimates for each day, the standard errors of the mean corrections are 0.2 cm in the east direction, 0.1 cm in the north direction, and 0.3 cm in the up direction. The formal uncertainties from the covariance matrix produced through combining the daily solutions are 0.4 cm in the east direction, 0.2 cm in the north direction, and 0.4 cm in the up direction. These are similar in size with the standard errors of the mean corrections. The true accuracy of the refined coordinates is probably somewhere between the scatter of the daily solutions and these two formal uncertainties.

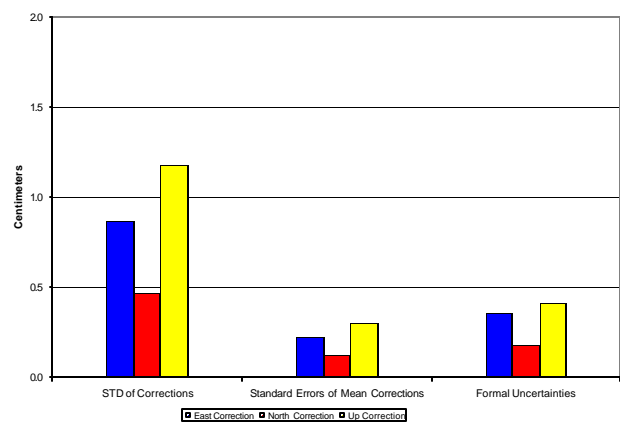


Figure 4. Error Characterization of Refined NIMA and Air Force Station Coordinates

Seven-parameter similarity transformations (three translations, a scale, and three rotations) were computed using least squares estimation to examine the systematic differences between the starting and refined estimates for the NIMA and Air Force station coordinates at the 2001.0 epoch. The estimated parameters, as given in Table 2, transform the starting coordinates representing the previous WGS 84 reference frame into the refined realization of the WGS 84 reference frame. The largest systematic difference occurs in the scale. This difference, -6.0 ppb, corresponds to about -3.8 cm at the Earth's surface. The largest rotation, -0.54 mas seen about the y-axis, corresponds to about 1.7 cm at the Earth's surface. In Figure 5, the overall RMS of the NIMA and Air Force station coordinate differences between the refined coordinates and the starting coordinates are compared with the overall RMS differences between the refined coordinates and the starting coordinates transformed using the seven-parameter transformation defined in Table 2. The RMS differences between the refined coordinates and the starting coordinates before the transformations are applied reflect the accuracy of the previous station coordinate solutions plus the accumulated errors from use of the plate motion model. This result corroborates the stated accuracy of better than five cm per component for the previous solution. The RMS differences between the refined coordinates and the starting coordinates after the transformations are applied reflect the removal of the systematic differences and are indicative of the level of the random errors in the previous solution.

Table 2. Transformation Parameters Between Starting and Refined NIMA/Air Force Station Coordinates

Translation (cm)			Scale (ppb)	Rotation (mas)		
x	y	z		x	y	z
-0.2	-0.0	0.8	-6.0	-0.26	-0.54	-0.39

1.0 ppb = 0.6 cm, 0.1 mas = 0.3 cm (Earth's surface)

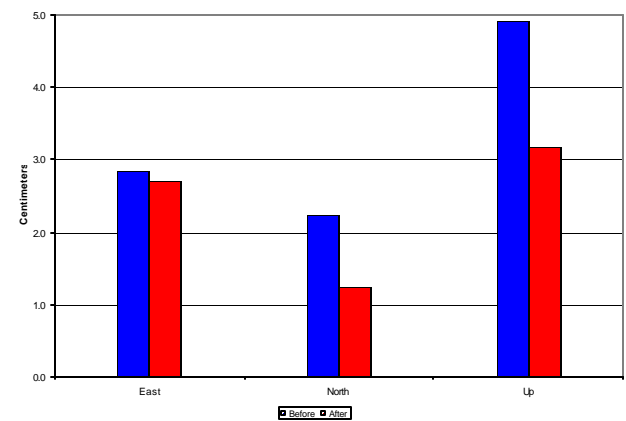


Figure 5. Comparison of RMS of NIMA and Air Force Station Coordinate Differences, Before vs After Seven-Parameter Transformations Applied

The differences between the Earth orientation values estimated simultaneously with the orbits and station coordinates associated with the 15 daily coordinate solutions and the IERS final values are reported in Table 3. The small mean differences in x and y indicate that the reference frame defined by the IGS fiducial stations was consistent with the IERS pole to this level.

Table 3. Differences Between Estimated Earth Orientation Using Refined Coordinates and the IERS Final Values

x (cm)		y (cm)		UT1-UTC rate (msec/day)	
Mean	STD	Mean	STD	Mean	STD
-0.3	0.3	0.3	0.5	0.019	0.034

EVALUATIONS

Extensive analyses were conducted in order to evaluate the quality of the refined NIMA and Air Force station coordinates and the inferred new realization of the WGS 84 reference frame. With the refined NIMA and Air Force station coordinates held fixed, the IGS station coordinates were estimated. Figure 6 gives the means and standard deviations of these corrections. These standard deviations are very similar to those over all of the NIMA and Air Force station coordinate corrections reported in Figure 4. For all cases, the mean adjustments were close to zero in the horizontal directions and approximately 0.5 cm in the up direction.

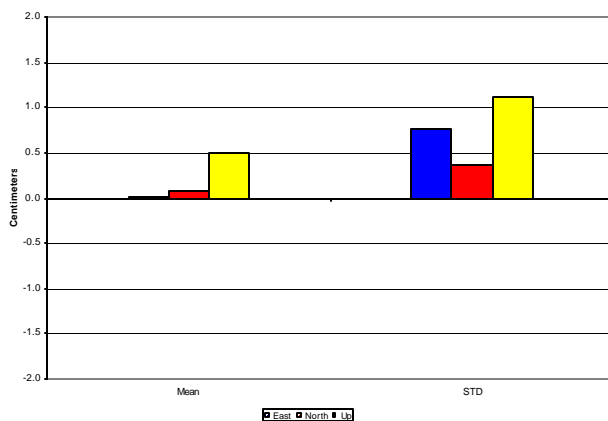


Figure 6. IGS Station Coordinate Corrections, Refined NIMA and Air Force Station Coordinates Held Fixed

The parameters defining the transformations between the starting and estimated IGS station coordinates are given in Table 4. The largest systematic difference occurs in the scale. This difference, -0.8 ppb, corresponds to about -0.5 cm at the Earth's surface. In Figure 7, the overall RMS of the IGS station coordinate differences between the estimated and the starting coordinates are compared with the overall RMS differences between the estimated

coordinates and the starting coordinates transformed using the seven-parameter transformation. Because only very small systematic differences exist between the original ITRF2000 IGS station coordinates and the estimated IGS station coordinates, little change is seen in the consistency of the coordinates. These results provide another indication that the WGS 84 reference frame defined by the refined NIMA and Air Force station coordinates is nearly coincident with the ITRF2000 reference frame.

Table 4. Transformation Parameters Between Starting and Estimated IGS Station Coordinates

Translation (cm)			Scale (ppb)	Rotation (mas)		
x	y	z		x	y	z
0.1	0.1	-0.1	-0.8	0.02	-0.03	-0.02

1.0 ppb = 0.6 cm, 0.1 mas = 0.3 cm (Earth's surface)

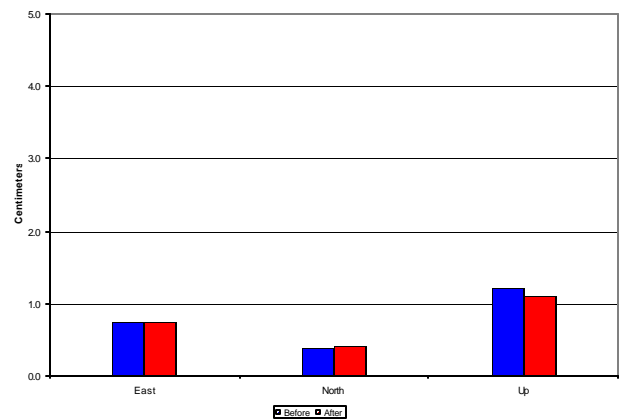


Figure 7. Comparison of RMS of IGS Station Coordinate Differences, Before vs After Seven-Parameter Transformations Applied

For the purpose of independently evaluating the quality of the refined coordinates, solutions for a limited subset of the NIMA stations were obtained from two different sources. These include solutions for England, Ecuador, New Zealand, and Australia from Dr. DeMets and the ITRF2000 solutions for China, Maspalomas, and Bahrain. These solutions were compared with the refined coordinates at appropriate epochs.

In support of evaluating and improving the modeling of plate motion, NIMA has been providing data from four of its GPS tracking stations used in the estimation of the precise GPS orbit and clock estimates to Dr. DeMets. Two stations, Ecuador and New Zealand, were selected due to their proximity to plate boundaries. The other two stations, England and Australia, are located within the relatively stable interiors of the Eurasian and Australian plates, respectively. The estimated velocities have been compared with the predicted velocities derived from the NNR-NUVEL1A plate motion model. Dr. DeMets' data

processing was performed with JPL's GIPSY software employing a point positioning technique for solving for daily site coordinates. Data were provided beginning on March 12, 1995 for Australia, January 2, 1996 for Ecuador, January 26, 1996 for England, and December 10, 1998 for New Zealand, and continuing to the present. JPL's precise orbit and clock estimates were used, as well as their daily transformations for aligning their loosely constrained daily site coordinates with the ITRF2000 reference frame. The estimates are relative to the reference epoch listed above for each site. The coordinate time series were used to derive the velocities. Using these velocities, the estimates at the reference epochs were updated to the 2001.0 epoch of the NIMA and Air Force coordinates. Figure 8 depicts the differences in the east, north, and up directions between the DeMets' estimates and the refined WGS 84 station coordinate estimates. For each of the four stations, the largest difference was significantly less than one cm per component. The largest difference was 0.8 cm in the east direction for Australia.

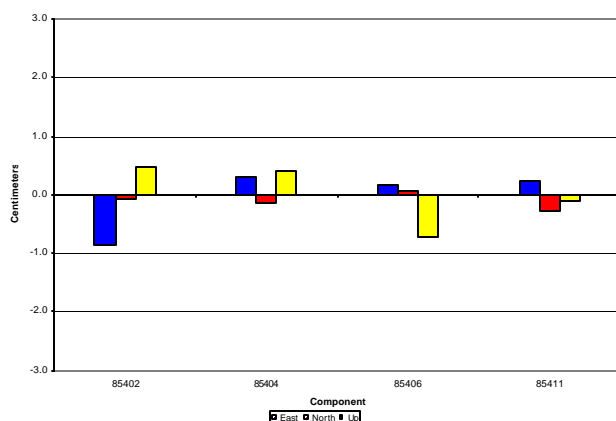


Figure 8. Differences Between the DeMets Coordinate Solutions and the Refined Station Coordinate Estimates

Although the IGS identifies Bahrain and Maspalomas as fiducial stations, the coordinates for these stations were estimated simultaneously with those for the other NIMA and Air Force stations. Additionally, data from the GPS tracking station in China have been provided to the IGS over a relatively short duration. Thus, ITRF2000 solutions were compared with the refined WGS 84 station coordinates for these three stations. Using the adopted velocities, the WGS 84 station coordinates were moved to an epoch of 1997.0. Figure 9 depicts the differences in the east, north, and up directions between the ITRF2000 estimates and the WGS 84 station coordinate estimates. The largest differences are in the vertical direction, with differences greater than one cm for both Maspalomas and China. The differences in the east and north directions are less than one cm for all three stations. The stated uncertainties in the ITRF2000 velocities are 0.2 cm/yr in the horizontal directions and 0.3 cm/yr in the vertical direction. The velocities for the site in China were derived from a relatively short data span, and probably have a significantly higher uncertainty associated with

them. During the selection of the velocities specific for each site, discrepancies were noted when comparing the ITRF2000 estimates with the JPL estimates for China. In particular, differences approaching 2.5 cm/yr were noted in the up direction. As the coordinates were moved over a span exceeding four years, the errors in the up direction velocity, contributed significant errors to the propagated positions.

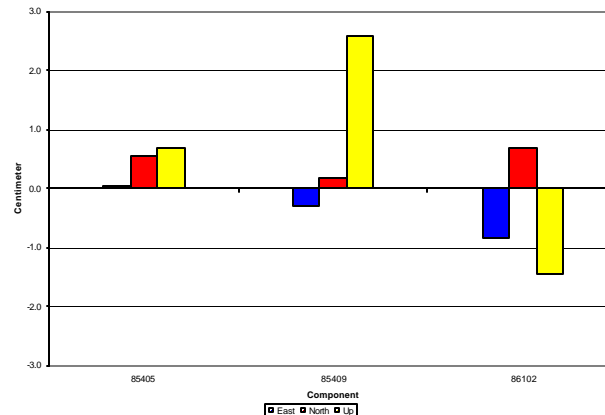


Figure 9. Differences Between the ITRF2000 Coordinate Solutions and the Refined Station Coordinate Estimates

NIMA routinely performs empirical comparisons between the WGS 84 reference frame and the ITRF reference frame. These comparisons include computing seven-parameter similarity transformations between the NIMA GPS precise orbits and the IGS final orbits and the differences between the NIMA Earth orientation parameters and the IERS final values. Comparisons have been performed on a daily basis since 1994 and have reflected successive refinements made to the WGS 84 reference frame. Comparisons beginning in 2001.0 and continuing through 2002.59 were examined to quantify the improvement in the level of agreement between the WGS 84 and ITRF reference frames (ITRF97 up until December of 2001, then ITRF2000) resulting from the implementation of the refined station coordinate set. A total of 383 days were used to generate the statistics before implementation of the refined coordinates, and a total of 195 days were used to generated the statistics after implementation.

Figures 10 through 12 compare the mean and standard deviations of the transformation parameters before and after the implementation of the refined station coordinates. The translations (Figures 10) represent the differences in the location of the origin of the two reference frames while the rotations (Figures 11) represent orientation differences. The scale parameter (Figures 12) represents a radial difference.

The largest systematic difference occurring in the translation along the z-axis was reduced from -2.2 to -0.6 cm. This translation was the largest of the three directions after the implementation of the refined station

coordinates. The largest systematic difference occurring in the rotation about the y-axis was reduced from 0.59 mas (corresponds to 1.8 cm at the Earth's surface) to -0.03 mas (-0.1 cm). There was, however, an increase in the mean rotation about the z-axis, from -0.06 to -0.28 mas (0.9 cm). The systematic difference occurring in the scale was reduced from -0.06 ppb (corresponds to less than 0.2 cm at GPS altitude) to -0.00 ppb. The levels of the standard deviations remained similar for all of the parameters.

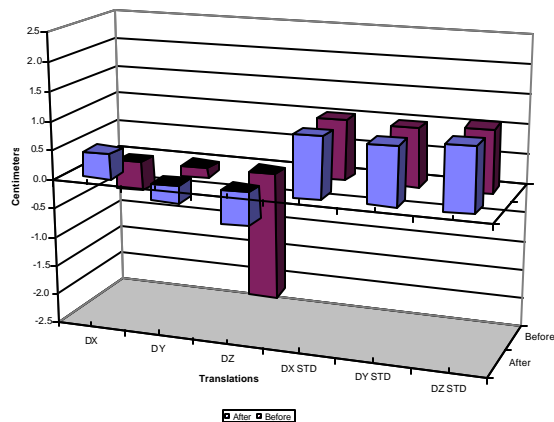


Figure 10. Mean and Standard Deviation of WGS 84 (G1150) to ITRF Translations Based on NIMA vs. IGS GPS Orbits

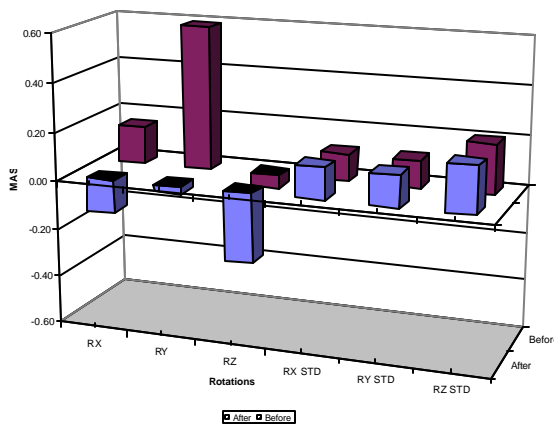


Figure 11. Mean and Standard Deviation of WGS 84 (G1150) to ITRF Rotations Based on NIMA vs. IGS GPS Orbits

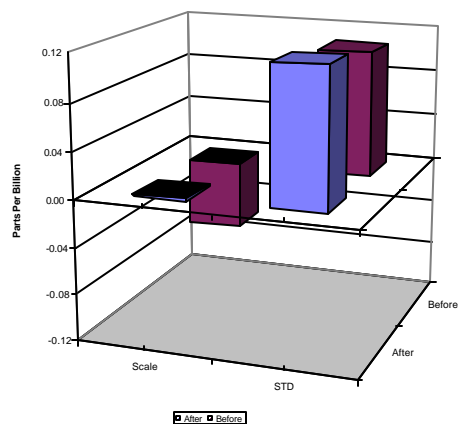


Figure 12. Mean and Standard Deviation of WGS 84 (G1150) to ITRF Scale Based on NIMA vs. IGS GPS Orbits

Figure 13 compare the mean and standard deviations of the differences between the NIMA Earth orientation parameters and the IERS final values. The systematic difference in x was reduced from 1.7 to 0.3 cm, with the systematic difference in the y essentially eliminated. The length of day (LOD) parameter remained similar, with a slight increase from 0.55 to 0.58 msec/day. The levels of the standard deviations remained similar for all of the parameters.

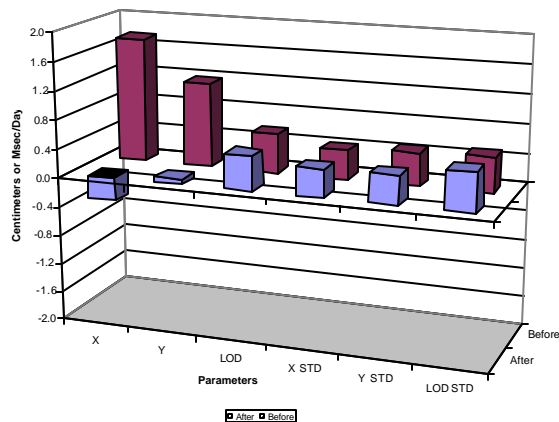


Figure 13. Mean and Standard Deviation of Earth Orientation Parameter Differences Based on NIMA vs. IERS Final Values

SUMMARY

To ensure the highest possible degree of accuracy and stability in the WGS 84 reference frame, a joint effort between NSWCD and NIMA was undertaken to refine the coordinates for the operational GPS tracking stations. The station coordinates were estimated while holding the ITRF2000 coordinates of a large subset of 49 of the IGS fiducial stations fixed using a 15-day data set collected in February 2001. The 15 independent daily solutions were formally combined to obtain the final coordinates. The adopted velocities for the stations were used to move the coordinates back to the 2001.0 epoch. This station coordinate set has been designated WGS 84 (G1150), since they were first implemented at NIMA starting GPS week 1150. The standard deviations of the daily solutions about their means were 0.9, 0.5, and 1.2 cm in the east, north, and up directions, respectively. The formal uncertainties in the solutions combined over all NIMA and Air Force stations were 0.4, 0.2, and 0.4 cm in the east, north, and up directions, respectively. Based on these results, the accuracy of each station coordinate component is estimated to be on the order of one cm, one sigma.

Extensive analyses were conducted in order to evaluate the quality of the refined station coordinates and resulting realization of the WGS 84 reference frame. With the refined coordinates held fixed, the coordinates of all of the IGS stations were estimated. The IGS station coordinate corrections had combined east, north, and up standard deviation values that were very similar to the standard deviations over all of the NIMA and Air Force station coordinate corrections. The only significant mean correction was 0.5 cm in the up direction. Comparisons against independent coordinate solutions for a subset of the NIMA stations also corroborate the stated overall accuracy of better than one cm per component. Seven-parameter similarity transformations were computed to examine systematic differences between the previous and the refined NIMA and Air Force station coordinates. A significant reduction in the RMS differences of the NIMA and Air Force station coordinates after the transformation was applied resulted from the removal of the systematic errors present in the previous coordinate solution. Additionally, the differences between the Earth orientation parameters derived simultaneously with the orbits and station coordinates and the IERS final values were very small.

Comparisons performed by NIMA with the operational products were used to quantify the improvement in the inferred WGS 84 reference frame based on the implementation of the refined station coordinate set. These included computing seven-parameter similarity transformations between the NIMA GPS precise orbits and the IGS final orbits and the differences between the

NIMA-estimated Earth orientation parameters and the IERS final values. The seven-parameter similarity transformations indicated an overall decrease in the systematic differences associated with the refined coordinates. The differences between the estimated Earth orientation parameters and the IERS final values were also significantly reduced. All of these results indicate the WGS 84 reference frame, as realized by the refined coordinates for the NIMA and Air Force tracking stations, is now essentially coincident with the ITRF2000. Currently, the orbit user range error of the precise GPS ephemerides produced by NIMA is approximately five cm.

A long-term procedure for refining station velocities is necessary if the accuracy of the refined WGS 84 station coordinate solutions is to be maintained. The adopted station velocities are currently being used to move the refined station coordinates from the adopted epoch of 2001.0 to the fit epoch in the generation of the precise GPS orbit and clock estimates at NIMA. In order to refine the station velocities, a procedure to generate a history of station coordinate estimates will be adopted. Within this procedure, the coordinates for the 18 NIMA and Air Force stations, including Maspalomas, will be routinely solved for with all of or a subset of the coordinates of the IGS fiducial stations held fixed. The resulting solutions will be formally combined to derive refined station velocity estimates. However, in order to have a robust solution, several solutions over an extended period of time are required. Until this requirement is met, the adopted velocities used in the station coordinate solution will continue to be used by NIMA.

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